Unified Shunt Capacitor Bank Control and Protection

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INTRODUCTION

Shunt capacitor banks are important in controlling and supporting the system voltage. In some areas, they may be required to prevent voltage collapse. Large capacitor banks which supply hundreds of megavars to the system are now in use. These banks consist of hundreds or even thousands of individual units interconnected to obtain the necessary voltage and VAR ratings.

Large banks require sensitive protection to alarm and trip for faulted units.

This paper presents a new relay for the protection and control of grounded shunt capacitor banks and discusses application considerations which are important in achieving the required sensitivity. The paper also describes an application of the device to a 500 kV, 342 MVAR shunt capacitor bank on the Bonneville Power Administration system.

PROTECTING SHUNT CAPACITOR BANKS

Shunt bank protection must cover or consider:

- Failure of individual capacitor units
- Fuse failures and blown fuses
- Faults on the capacitor bank frames or structure
- Faults on the system external to the capacitor bank.

ANSI/IEEE C37.99-1980, the IEEE Guide for Protection of Shunt Capacitor Banks (Reference 1), covers a very large range of fused bank configurations, protection requirements, and protection methods.

More recently, fuseless banks have begun to appear (Reference 2). These have significant design, protection and operation advantages, made possible by film/foil capacitor units.

Shunt Capacitor Bank Description

Banks typically consist of series-parallel combinations of capacitor "cans" or "units." Each unit contains several smaller capacitors or sections, each having a typical nominal voltage rating of 1600 volts. Older capacitors are made of foil electrodes separated by dielectric layers and impregnated with oil. All new capacitors are made of foil electrodes separated by a dielectric of thin polypropylene sheets.

The referenced standard IEEE C37.99 states that capacitor units shall be capable of indefinite operation at 110% of the nameplate voltage rating.

Virtually all high-voltage banks are wye-connected. Although the neutral can be grounded or ungrounded, this paper concentrates on grounded wye-connected banks.

Fused banks consist of a series connection of numerous groups or layers. Each group contains a number of capacitor cans, or units, in parallel. Fuses protect each individual unit. Figure 1 shows one phase of a fused bank, with P units per group and S groups in series. The figure also shows two potential transformers. The bus PT is used for control and protection, while the tap PT is used for differential protection by comparing the bus and tap voltages.

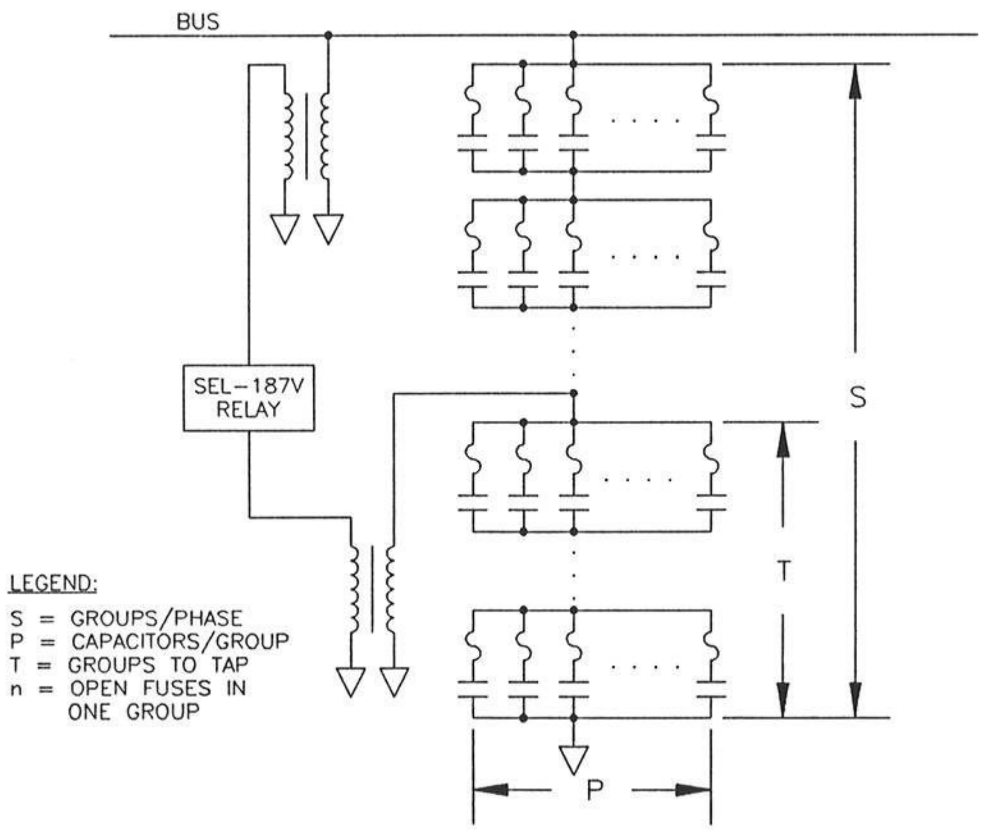


Figure 1: Fused Capacitor Bank With Voltage - Differential Protection

Fuseless banks consist of one or more series strings of units, per phase. If a section in a unit fails, the electrodes weld together solidly enough to safely carry rated current. Since there are no units in parallel, it is not necessary to isolate the failed unit.

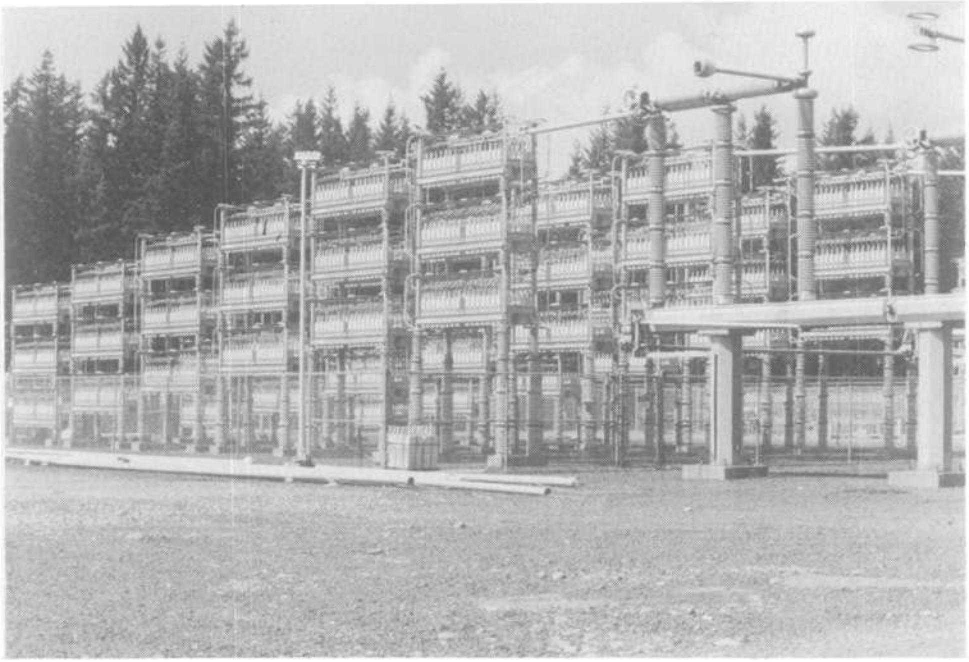


Figure 2: 500 kV Grounded-Wye Shunt Capacitor Bank

Faults

A large variety of faults is possible. Many possibilities are mentioned below, along with the protective measures capable of handling them.

Shorted Unit in a Fused Bank

A unit normally fails at a point on wave where voltage is substantial. The system and the units in parallel with the shorted unit deliver energy to the fuse. The fuse in series with the shorted unit melts almost instantaneously.

In the less probable case where a unit is shorted upon energization or otherwise shorts at a voltage zero, the fuse of the shorted unit carries P times the normal operating current, where P is the number of units in parallel. In this case, fuse clearing can be expected in some fraction of a second.

The possibility of case rupture limits the number of units which can be safely paralleled. On the other hand, an open fuse increases the voltage across the remaining cans by approximately P/(P-1), so more than ten cans must be connected in parallel to ensure that one open fuse does not leave more than a 10% overvoltage on the remaining units in that group.

A differential voltage relay comparing the per-unit voltages at the bus and a tap point can detect a single open fuse in all but the largest banks.

Shorted Unit in an Unfused Bank

Unfused banks consist of series strings of units. There are no parallel combinations of units, so case rupture due to the energy delivered from parallel cans is not a concern. Differential voltage protection can again detect the unbalance produced by shorted units.

Shorted Group or Fuse Failure

Protection must cover failure of a fuse to clear and faults across any group. Fuses in the bank offer no protection for these events. The voltage across the remaining groups increases to S/(S-1), where S is the number of series-connected groups or layers. Fortunately, fuse failures and group faults are easily detected by differential protection, even in the largest banks.

A shorted group or fuse failure should be the first priority in protection. Fast tripping is desired to limit overvoltage on remaining groups and prevent the fault from becoming more serious.

Ground Fault in the Bank

A fault to ground could occur, which shorts out one to all of the groups in that phase. If a ground fault occurs near the bottom of the bank, the additional current produced may be very small. If the fault is near the top, the current can be large enough to quickly melt fuses. However, the fuses may not clear if the fault to ground is high enough up the bank to exceed recovery voltage capabilities of the fuses. Ground faults anywhere except at the top of the bank produce differential voltage signals.

If the fault is at the top, the bus and tap voltages remain equal, and no differential voltage develops. Phase overcurrent protection set to several multiples of rated bank current is sufficient to detect this fault.

Phase Fault in the Bank

Phase faults produce differential voltage, except if the fault is at the top. In the latter case, the overcurrent protection mentioned above must detect the fault.

A device with limited interrupting capacity, such as a circuit switcher, is often used to control the bank. It can be safely tripped for most faults in the bank. However, overcurrent protection coordinated with the interrupting capacity of the circuit switcher should be considered to block tripping of the circuit switcher and operate devices capable of clearing the fault, for faults beyond the rating of the circuit switcher.

Voltage Differential Protection

Figure 1 shows one phase of a fused capacitor bank. Under normal conditions the groups of capacitor units have nearly identical impedances and the bus voltage divides evenly among all groups in series. Under most fault conditions, the voltage no longer divides evenly.

Table 1: General Equations for Grounded-Wye Banks		
Tap Voltage Change (pu) for 10% Group Overvoltage	$dV10 = \frac{0.1}{S - 1}$	Equation 1
Fuse Operations (n) Necessary to Cause a 10% Group Overvoltage	$n = \frac{S * P}{11 * (S - 1)}$	Equation 2
Tap Voltage Change (pu) When n Fuses Open in One Group Above the Tap	$dV(n) = \frac{n}{S * (P - n) + n}$	Equation 3
Tap Voltage Change (pu) When n Fuses Open in One Group Below the Tap	$dVT(n) = \frac{n * (1 - S/T)}{S * (P - n) + n}$	Equation 4
Voltage (pu) Across Capacitors in Group with n Open Fuses	$Vc(n) = \frac{S * P}{S * (P - n) + n}$	Equation 5

There are several ways to develop a differential voltage. The figure shows potential transformers measuring voltages at the bus and at an intermediate point in the bank. Table 1 gives equations for differential voltages and other conditions pertaining to a grounded fused shunt capacitor bank.

If the bank is divided into two or more series strings or otherwise split into sections, the voltages at intermediate points in the strings or sections can be compared. If there are only two strings, however, there are protection "holes:" equal impedance changes above or below the taps cannot be detected. With more than two strings and tap voltages compared from string to string, only those faults which produced the same impedance changes in all three strings would be detected: this is probably an acceptable risk.

Unbalance Protection

Unbalance protection is a simpler alternative to differential protection. Where differential protection requires six inputs to cover a three-phase bank, an unbalance relay requires only one to three inputs.

One approach to unbalance protection monitors the neutral current for the bank. Unfortunately, natural system unbalance and faults produce neutral currents. Due to tolerances, differences in the net capacitance of the three phases also produce neutral currents.

Another approach is to compose a phasor sum of capacitor bank tap voltages. The idea is that when blown fuses produce unbalance, the phasor sum will deviate far enough from zero to be detected. Although the scaling factors for each of the three phases could be adjusted to null out system, measurement, and bank unbalance, the scheme still responds to system unbalance, because such unbalance is not static.

Unbalance elements respond to line and system faults, requiring long coordinating time delays. On the other hand, the differential elements emphasized in this paper do not respond to natural system unbalance or faults, and measurement unbalance can be nulled out.

PROTECTIVE RELAY DESIGN

The development project had several objectives:

1. Replace the differential protection previously provided by the MTY relay.

2. Add instantaneous and definite-time overvoltage protection.

3. Improve on the security, testability, and settability. In particular, make balancing the differential scheme easier.

4. Include voltage control as well as bank protection to simplify installations.

5. Provide versatility for broad voltage-relaying application through programmable mask logic and other tools.

Design Concepts

Three-phase differential protection requires six voltage inputs. Three-phase voltage control requires three voltage inputs. We elected to design one instrument with two sets of three-phase voltage inputs (X and Y) which could be used as two three-phase voltage relays and simultaneously as a differential relay. Each of the two voltage relays provides under/overvoltage protection as well as voltage control.

This design approach yielded a relay which can control and protect a capacitor bank as well as a shunt reactor.

Relay Hardware

We chose to use field-proven digital relay hardware as the basis for the design. The hardware samples six voltage inputs four times per cycle and processes the samples in a microprocessor.

Signal Processing

Inputs from voltage transformers are stepped down 10:1 inside the relay through small auxiliary transformers. The voltages are further reduced through resistive dividers and limited using MOVs.

The hardware then lowpass filters the six voltage inputs. The system uses a passive pole at about 1000 Hz and an active pole pair near 85 Hz. Third harmonic components are attenuated to about 1/7 of their input levels.

After the signals are sampled, they are digitally filtered. We used the double-differentiator-smoother or CAL filter:

$P = X1 - X2 - X3 + X4$, where X1...X4 are the newest four samples.

The digital filter rejects dc offset and has zeros at double multiples of system frequency. Digital and analog filtering provide a net bandpass process centered on system frequency.

The present and previous quarter-cycle values of P form the (x, y) components representing each voltage as a phasor. The computer determines the magnitude of each phasor using the square root of the sum of the component's squares.

Each magnitude is smoothed by a first-order lowpass filter:

$$y(k) = 0.75\ y(k-1) + 0.25\ u(k)$$

where k counts ¼ cycle steps,
u(k) is the unsmoothed magnitude input to the filter
y(k) is the filter output of smoothed magnitude.

The smoothing provided by this filter reduces quantization and other noise.

Voltage Reference and Temperature Dependence

Because the relay is intended for voltage control as well as capacitor bank protection, a precise voltage reference is required. The relay uses the internal buried-zener reference diode in the analog-to-digital converter as the reference.

We characterized the temperature dependence of voltage measurement by applying a constant voltage to the relay and reading its voltage measurement using the relay METER function while moving the temperature from -20 to +60° Celsius. We determined that the temperature dependence is about +6 mV/° Celsius at a nominal input voltage of 70 volts. A one percent change in the setpoint would require a temperature change of about 116° Celsius.

This applies to all voltage elements, whether intended for voltage control or protection.

Elements for Voltage Control Measure the Average System Voltage

The relay contains two overvoltage and two undervoltage elements intended for voltage control. Each of these four elements responds to the magnitude-average three-phase voltage. Because of the filtering mentioned earlier, the relay measures (and controls) the three-phase average fundamental-frequency voltage.

Elements for Protection Measure the Individual Phases

There are overvoltage and undervoltage elements for each of the six voltage inputs. These respond to the fundamental-frequency component of the voltage applied to each input.

Differential Elements Respond to Magnitude Differences

A current differential element, if used for transformer protection, responds to the phasor sum of all currents into the zone of protection for that relay. In doing this, the current differential relay is performing Kirchoff's current law on the protected zone. Normally, high sensitivity is not a requirement.

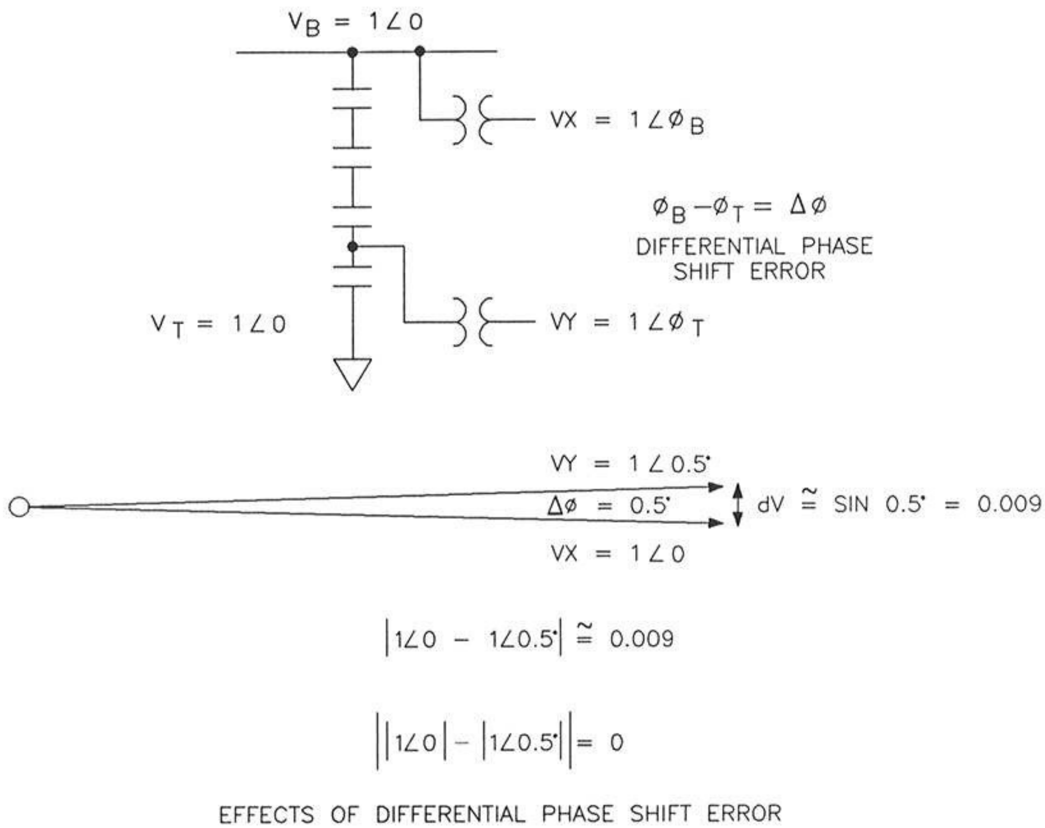


Figure 3: Differential Phase Shift Error Causes Significant Differential Voltage Signal Unless Magnitudes Are Used

The shunt capacitor differential protection problem is different (please refer to Figure 3). We are looking for minute changes in the performance of a string of capacitors acting as a voltage divider. The voltage measurement devices are of vastly different ratios and may have very different designs. For example, the bus voltage measurement may come from a CCVT, while the tap voltage measurement may come from a wound PT or potential device. Different phase shifts in the bus and tap PTs could produce error signals in a differential relay which responds to the phasor difference between the bus and tap voltages. For example, suppose that the bus and tap PTs produce 70 volts for the relay under normal balanced conditions, but there is a 0.5 degree difference between the phase shifts of the two voltage measurements. The differential voltage is about sin (0.5) = 0.009 pu or 0.6 volts. This is on the order of the differential signal that would result from a single blown fuse in a 100-unit bank!

We could overcome this limitation on sensitivity by providing a null adjustment for phase angle as well as for magnitude. However, there is very little information we can use in the phase angle, so it can be ignored. Short circuits and blown fuses in the bank move the magnitudes of the voltages, but the phase relationships stay generally constant. An exception is a phase-to-phase fault within the bank: it causes a significant phase shift between the bus and tap voltages. Fortunately this type of fault causes a significant magnitude shift.

For these reasons, we designed the relay to respond to the differences between the magnitudes of its inputs rather than the phasor differences.

The computer forms three magnitude-differential voltages. For example, for phase A, the differential voltage is:

$$dVA = |VAX| - KA\,|VAY|$$

where dVA is the differential A-phase voltage
VAX is the A-phase input from the X set of potentials (e.g. bus)
VAY is the A-phase input from the Y set of potentials (e.g. tap)
kA is an adjustable proportionality constant.

The adjustments KA, KB and KC permit precise nulling of the differential voltages. In fact, the relay has a feature whereby it measures what values KA, KB and KC should have in order to null out the difference voltages.

Every attempt must be made to minimize the effects of quantization noise and scaling errors inside the relay. The relay should also accommodate noise and errors which occur outside the relay as much as possible.

The difference voltage dVA is smoothed by a digital filter identical to that used on the phase voltages. The difference voltage finally tested is the smoothed difference between two smoothed voltage measurements. The smoothing does introduce some delay, but greatly adds to the security of the relay and reduces the minimum setting of the differential elements to under 0.2 volts.

Relay Logic

Figures 4 through 8 illustrate the straightforward relay logic.

Figure 4 shows the instantaneous overvoltage and undervoltage elements and logic. Using the programmable-mask logic, an overvoltage condition on any combination of the six inputs could be programmed to cause a trip. In capacitor protection, these elements could be set to trip the bank for a severe overvoltage condition, e.g. 1.2 per unit.

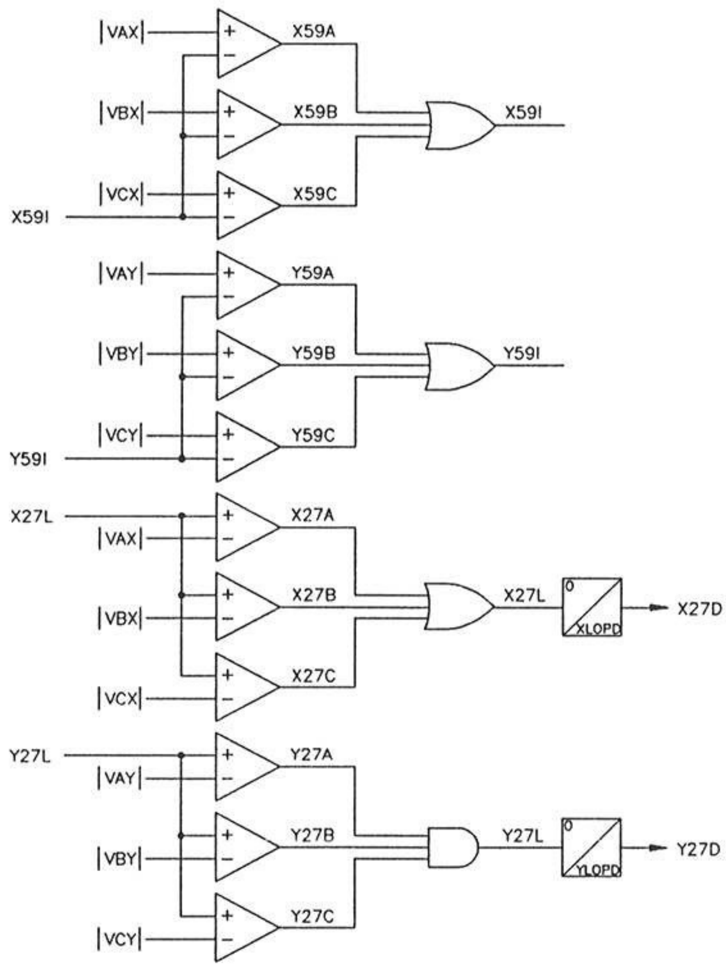


Figure 4: Overvoltage Elements / Undervoltage Elements and Logic

The undervoltage elements from the X-potentials are or'ed together and drive a time-delay dropout timer intended for loss-of-potential blocking of the differential elements. The Y-side "ands" the Y-undervoltage conditions together for a loss-of-potential condition. The OR of X-potentials versus AND of Y-potentials is the only difference between the X and Y sides of the relay. When the relay is applied to protect a capacitor bank, bus potentials should be applied to the X input and tap potentials to the Y input. Loss of a single phase of bus potential immediately blocks the differential relay logic; loss of three-phase tap potentials (as occurs every time control switches the bank off) is required to block the differential protection.

Definite-time overvoltage elements (Figure 5) can be used to initiate a trip for less-severe overvoltage conditions with the security of definite-time delay. Tripping might be set for several minutes at a voltage of 1.1 per unit (the upper limit of continuous operation of the capacitors.)

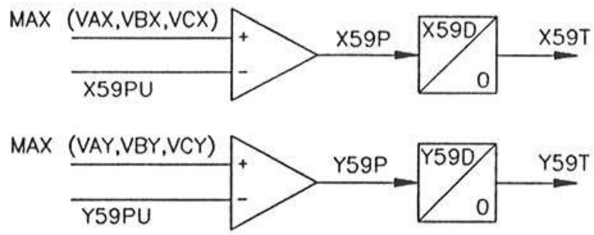


Figure 5: Definite-Time Overvoltage Logic

Figure 6 shows one phase of the voltage differential protection. The difference voltage is formed, considering a scale factor (KA for phase A) and tested against two thresholds (87AT, 87AA). Each phase has separate scale factors and thresholds. Loss-of-potential blocking disables the differential elements for single-phase losses of X-potentials or three-phase losses of Y-potentials. The time-delay dropout timers (LOPD, XLOPD and YLOPD) permit inclusion of sufficient time for voltages to settle down after bank energization or other restorations or applications of voltage. Keep in mind that the differential elements might need to be set quite sensitively (e.g. less than 0.01 pu in many cases), so ample settling time should be allowed for CCVT voltage measurements and the relay filtering.

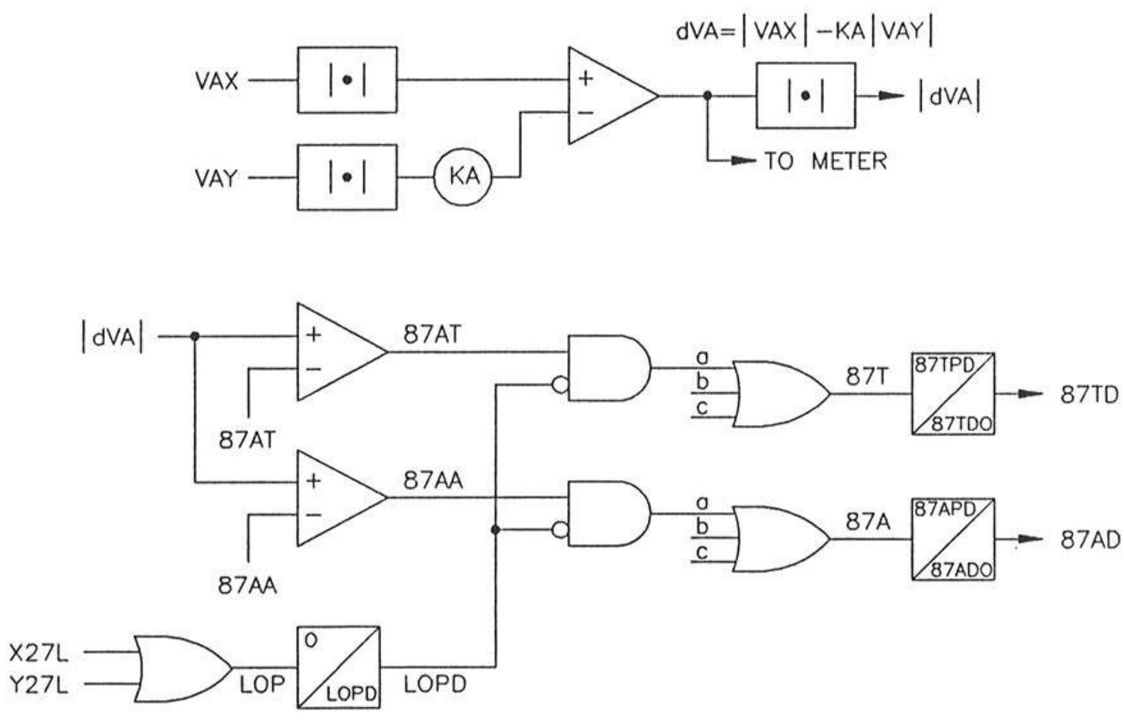


Figure 6: Voltage Differential Protection (Per Phase)

Differential signals exceeding their thresholds on any phase operate timers, which require minimum duration of the signals, and stretch the dropout time. The two outputs 87TD and 87AD can be used to trip and/or alarm on unbalanced conditions.

The signed difference voltages (dVA, dVB, dVC) are used by the METER command, so we can inspect the difference voltage sensed at any given time.

Figure 7 shows the two voltage control logic schemes. Inputs V1 and V2 are taken from the X or Y side, depending on the voltage control setting selected.

When the differential functions are used, voltage control would normally use the X-potentials. The relay may be set so that V1 = V2 = VX. Both voltage control schemes then operate from the bus voltage, but provide independent levels and time delays.

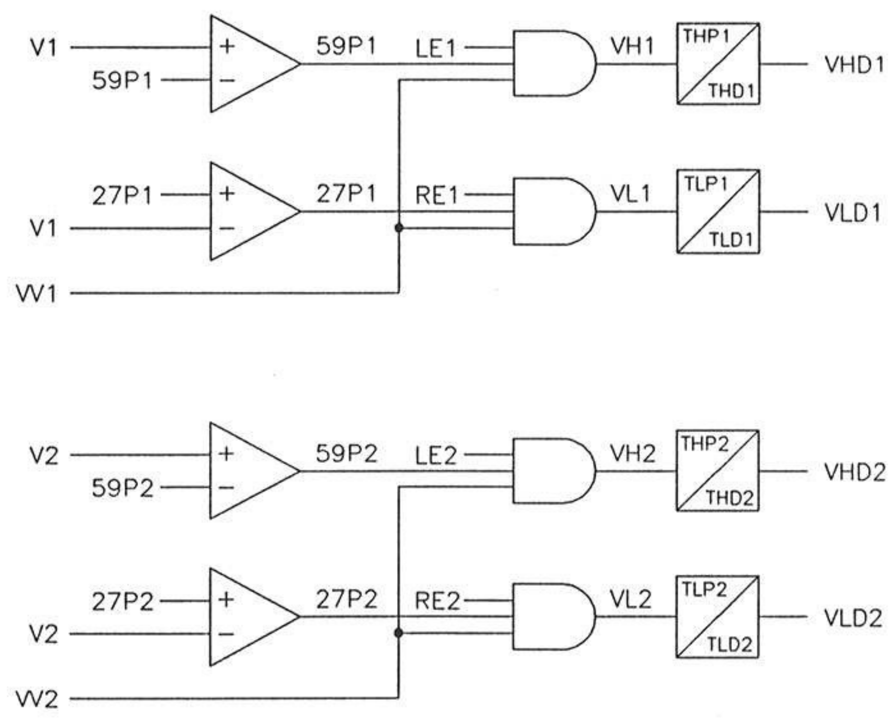


Figure 7: Voltage Control Logic

If the differential functions are not needed and the relay is to be used as two completely independent voltage relays, the instrument can be set so V1 = VX and V2 = VY, where VX and VY are the three-phase average voltages. Another option is that the relay automatically chooses VX or VY depending on loss-of-potential conditions.

The logic of Figure 8 can be used to prevent the voltage control scheme from oscillating. The logic detects voltage control instability by signalling a high voltage condition immediately after a voltage increase. For example, suppose the difference between the raise and lower voltage thresholds is 0.5 volt, but the insertion of the capacitor bank increases the voltage by one volt. If the voltage drops just below the raise-voltage threshold, the bank is energized after a time delay. The signal to energize the bank is stretched with a time-delay dropout timer, providing an indication that the voltage "just raised." In our example, inserting the bank increases the voltage one volt, which brings it above the voltage-lower threshold. We assumed the voltage-lower threshold to be only 0.5 volt above the raise-voltage threshold. So, inserting the bank caused an overvoltage condition, and the lower-voltage threshold timer begins running.

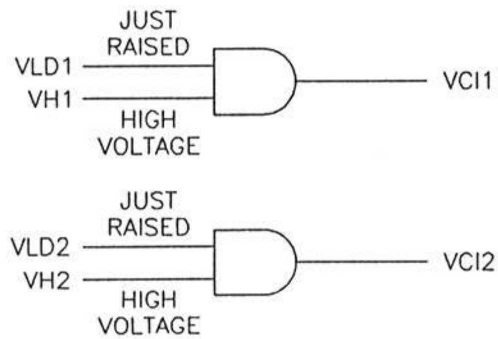


Figure 8: Voltage Control Instability Logic

Relay Testing and Setting

The relay elements and timers are set using the SET command. The relay uses programmable mask logic to define output relay functions. Table 2 shows the contents of the 48-bit relay word. Any one or combination of these 48 bits can be chosen to control any output relay or trigger event reports, using the LOGIC command.

The TARGET command permits local and remote inspection of any relay contact inputs, contact outputs, elements, and timers.

The METER command shows the six input voltages and the three differential voltages. The sign of the differential voltage is retained, so the sense of any unbalance is easily observed.

The KSET command automatically calculates and optionally adjusts the voltage ratio adjustment factors, making it easy to balance the relay, even remotely via communications.

Sensitive differential settings should be more reliable when using the METER command to inspect the differential voltages and the KSET command to balance the relay when required. One danger in any differential scheme lies in adjusting out differences which are legitimate signals. For example, a bank may be so large that the loss of a single unit is impossible to detect reliably. A unit may be lost and an operator rebalances the relay. Now the relay is insensitive to the next unit loss, which might otherwise be detectable.

A PULSE command permits testing of the outputs by pulsing on a selected output for one second.

Table 2: Relay Word Bit Summary Table

Row #1		Row #4	
X59A	Source X A-Phase Overvoltage	VH1	Voltage Control Scheme 1, Voltage High State
X59B	Source X B-Phase Overvoltage	VL1	Voltage Control Scheme 1, Voltage Low State
X59C	Source X C-Phase Overvoltage	VH2	Voltage Control Scheme 2, Voltage High State
X59I	Source X Any Phase Overvoltage	VL2	Voltage Control Scheme 2, Voltage Low State
Y59A	Source Y A-Phase Overvoltage	VHD1	Scheme 1, Time-delayed Voltage High
Y59B	Source Y B-Phase Overvoltage	VLD1	Scheme 1, Time-delayed Voltage Low
Y59C	Source Y C-Phase Overvoltage	VHD2	Scheme 2, Time-delayed Voltage High
Y59I	Source Y Any Phase Overvoltage	VLD2	Scheme 2, Time-delayed Voltage Low
Row #2		**Row #5**	
X27A	Source X A-Phase Undervoltage	X27D	Source X, Time-delayed Dropout Undervoltage
X27B	Source X B-Phase Undervoltage	Y27D	Source Y, Time-delayed Dropout Undervoltage
X27C	Source X C-Phase Undervoltage	LOP	Instantaneous Loss-of-Potential, Either Source
X27L	Source X Any Phase Undervoltage	LOPD	Time-delayed Dropout Loss-of-Potential, Either Source
Y27A	Source Y A-Phase Undervoltage	VCI1	Scheme 1 Voltage Control Instability Detected
Y27B	Source Y B-Phase Undervoltage	VCI2	Scheme 2 Voltage Control Instability Detected
Y27C	Source Y C-Phase Undervoltage	87T	Instantaneous Differential Overvoltage Trip
Y27L	Source Y Three-phase Undervoltage	87A	Instantaneous Differential Overvoltage Alarm
Row #3		**Row #6**	
X59P	Source X Definite-Time Overvoltage Pickup	87AT	A-Phase Differential Overvoltage Trip
X59T	Source X Definite-Time Overvoltage Trip	87AA	A-Phase Differential Overvoltage Alarm
Y59P	Source Y Definite-Time Overvoltage Pickup	87BT	B-Phase Differential Overvoltage Trip
Y59T	Source Y Definite-Time Overvoltage Trip	87BA	B-Phase Differential Overvoltage Alarm
59P1	Magnitude-Average Overvoltage, Scheme 1	87CT	C-Phase Differential Overvoltage Trip
27P1	Magnitude-Average Undervoltage, Scheme 1	87CA	C-Phase Differential Overvoltage Alarm
59P2	Magnitude-Average Overvoltage, Scheme 2	87TD	Time-delayed Differential Overvoltage Trip
27P2	Magnitude-Average Undervoltage, Scheme 2	87AD	Time-delayed Differential Overvoltage Alarm

ELEMENT CHARACTERISTICS

We characterized all relay elements using computer-controlled test equipment and totally automated testing procedures. The testing process automated setting the relay through its serial communications port, programming the test equipment, initiating the test, and retrieving and storing the data.

Figure 9 is a block diagram of the test setup. The computer runs **Doble's ProTest** program to control the test equipment, as directed by a commercial communications software package called **RelayGold** (its name includes the word "relay" only by coincidence). **RelayGold** also handles the communications with the digital relay. We wrote **RelayGold** script files to handle all communications directly with the relay and through **ProTest** to the test equipment.

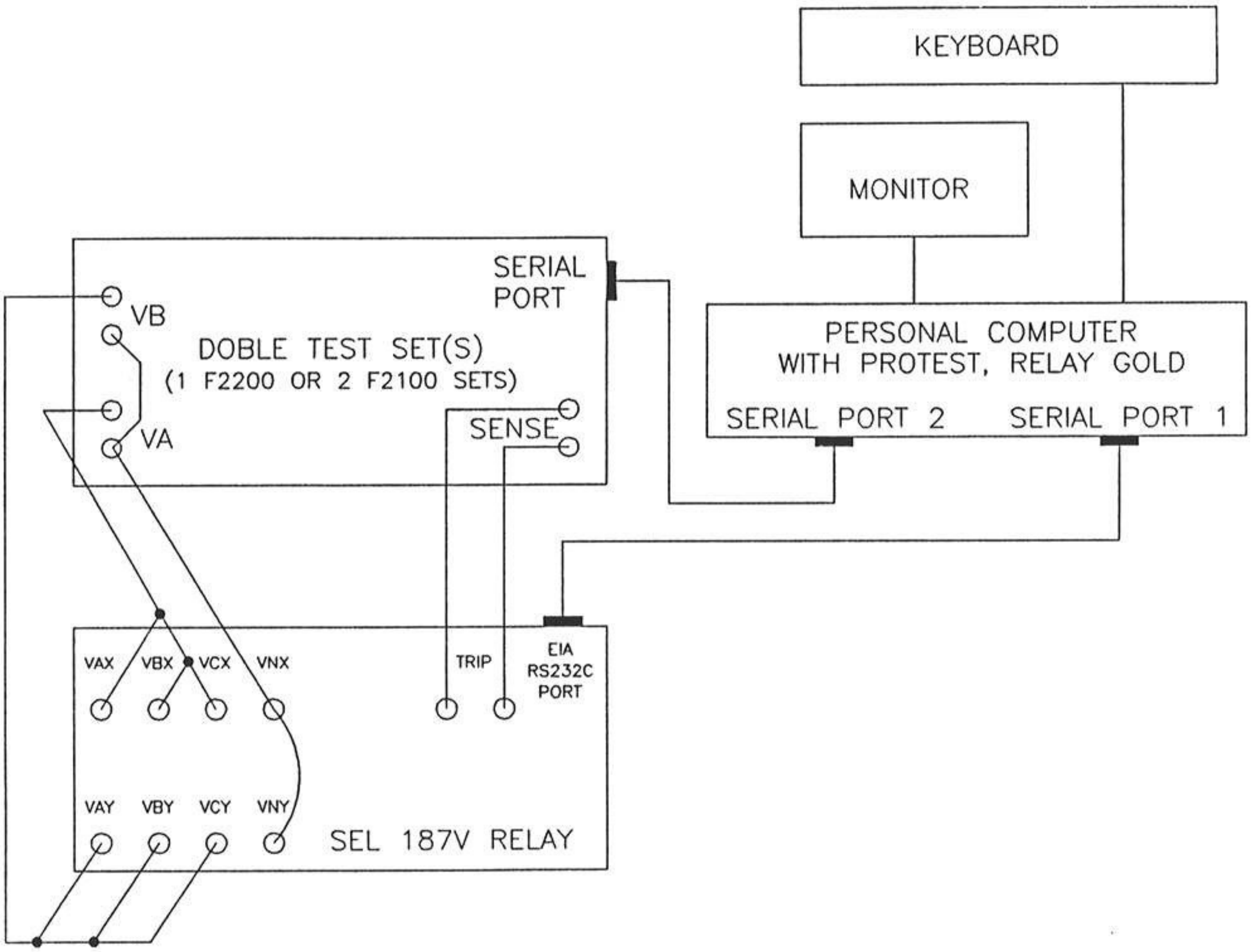


Figure 9: Block Diagram for Automated Tests

The automated test setup permits completion of more testing in the same amount of time with much less human attention. There is no question about how the test was performed because test details are part of the script. Tests repeat accurately every time, so retesting after modifications is more convenient and meaningful. Engineers and technicians spend time preparing test plans and analyzing results, not conducting tests.

Element Dynamic Characteristics

Figures 10, 11, and 12 provide dynamic characteristics for the overvoltage, undervoltage, and differential voltage elements.

Figure 10 shows the dynamic characteristic for the overvoltage elements. We started with an initial condition of zero volts, switched on a voltage above the pickup voltage, and measured the time from application of voltage to closure of a contact programmed to follow the overvoltage element. The element requires several cycles to pick up for a 10% overvoltage condition if the initial condition is zero. Initial conditions near the operating point substantially reduce the operating time.

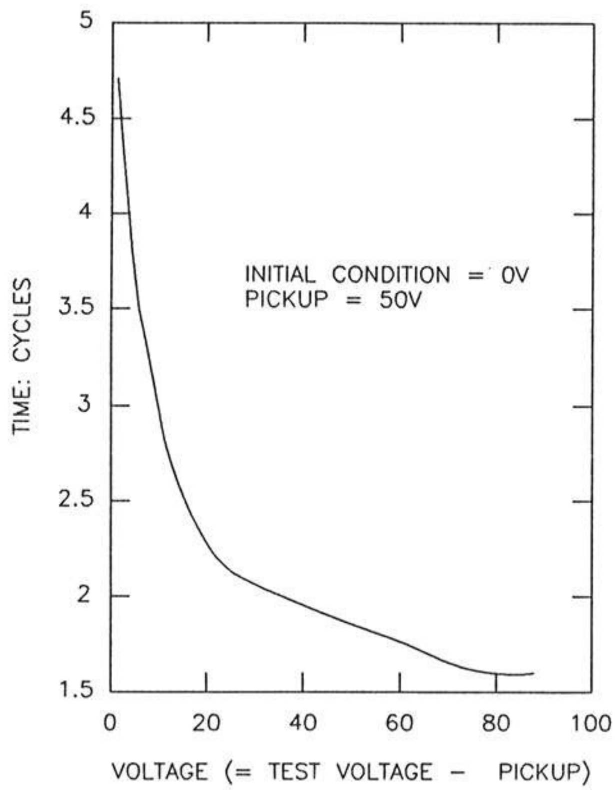


Figure 10: Overvoltage Element Dynamic Response

Figure 11 shows the operating time for the undervoltage elements starting with a voltage of 20 volts above the element setting.

Figure 12 shows the operating time for the differential elements. We obtained this curve by holding VY at 70 volts and starting with VX at 70 volts. We suddenly dropped VX to cause a voltage difference and measured the time for the element (set to one volt) to operate.

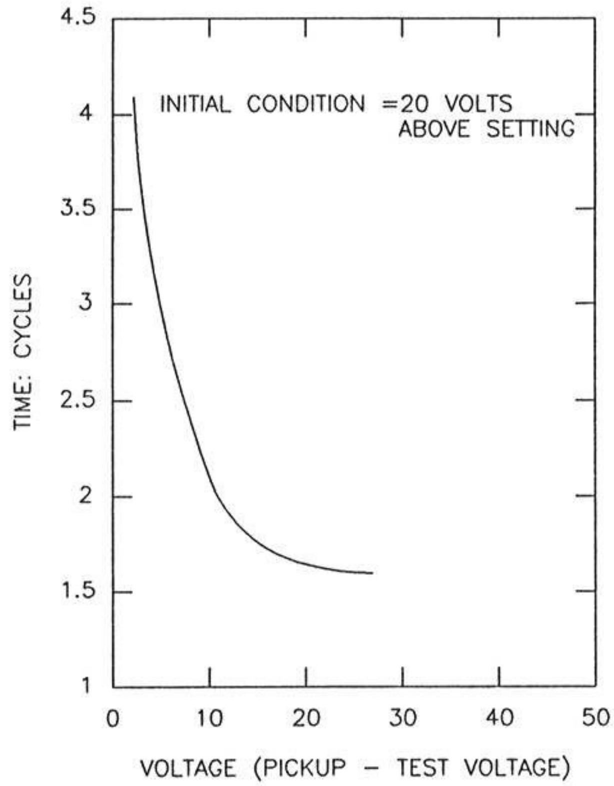


Figure 11: Undervoltage Element Dynamic Response

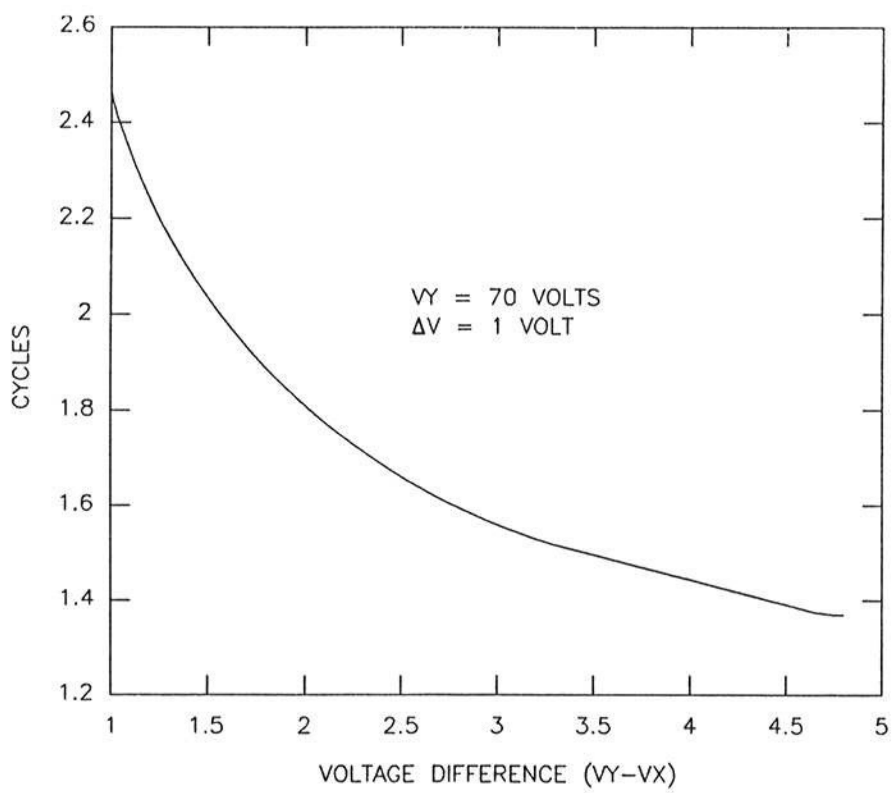


Figure 12: Dynamic Response of Differential Elements

The inverse-time appearance of the curves stems in part from the CAL digital filter and mainly from the magnitude-smoothing filter. Smoothing adds to element security, which is especially important for the differential elements.

Differential Element Stability

The purpose of this test was to determine the minimum stable differential element setting. The resolution of voltage is 0.03 volts; however, the differential elements may not be set to this level because of quantization and other noise in the relay.

We applied 115 Vac to all six phases and adjusted the differential elements upward in 0.03 steps from 0.03 until we observed no operations in a five-minute period. This occurred at a differential setting of 0.13 volts or four steps of resolution. We left the relay set to trip instantaneously at 0.13 volts and alarm instantaneously at 0.09 volts (three steps of resolution) for 48 hours. Four alarms and no trips occurred.

This test suggests minimum settings of 0.12 volt with 30 cycles delay for alarming and 0.15 volt with 10 cycles of delay for tripping. System and installation considerations are likely to produce higher limits to practical minimum settings. This paper discusses some of these considerations later.

Phase Angle Independence of the Differential Elements

The purpose of this test was to ensure that differential elements are immune to phase angle differences between the voltage inputs. We set a differential element to 0.25 volt and held VX constant at 67 volts. We also set VY to 67 volts, but varied its angle in one-degree steps from 0 to 90 degrees while monitoring the element state. No operations were detected. We repeated the tests for differential element settings of 0.19, 0.16, and 0.12 volts without problem. At a differential element setting of 0.09 volts (the differential element stability limit), operations were noted.

We concluded that the differential elements are practically immune to phase differences between their inputs.

Harmonic Rejection

We measured the harmonic response of the voltage elements by applying 70 volts at the fundamental and the first five harmonics and observing METER command output. The results appear on the next page:

Frequency	Per Unit Response
60 Hz	1.00
120	0.00
180	0.16
240	0.00
300	0.05

Note the zero response at even harmonics, as expected from the CAL filter. The analog lowpass filter provides the attenuation of the odd harmonics.

GENERAL APPLICATION CONSIDERATIONS

Fused Shunt Bank Protection

Assuming the bus and tap PTs are available, determine the differential voltage produced by the loss of one unit, using Equation 3 of Table 1. Set the differential alarm elements to pick up at 0.5 to 0.8 of this voltage include a time delay of several minutes to avoid nuisance alarms, especially in large banks. Recall that the minimum recommended setting for the differential element is 0.15 volt. This corresponds to 0.15 / 115 = 0.0013 per unit assuming a 115-volt PT secondary. The voltage difference must be 1/0.8 times this, or 0.00163 per unit. Referring to Equation 3 of Table 1 and approximating the denominator by SP, we find that the relay can detect one unit out in a bank with up to SP = 1/0.00163 = 613 units. The overall relaying system may not perform this well, depending on other sources of error. This paper explores these sources later.

Set the tripping differential element for a 10% group overvoltage, as given by Equation 1 of Table 1. Coordinate the time delay of this trip with the clearing time of a fuse, assuming the fuse operates on 60 Hz current (worst case time) instead of the energy from the parallel units.

Set the instantaneous and definite time overvoltage elements for the bus and tap to operate at around 20% and 10% of rated voltage. Set the definite time delay associated with the 10% overvoltage setting conservatively, considering the operating time permitted for a 20% overvoltage. This will probably be several minutes. The logic here is to first ensure that the bank trips instantaneously for overvoltages greater than 20%. The system can withstand overvoltages between 10% and 20% for times up to the maximum time permitted at 20%.

Provide ample loss-of-potential dropout delay. This allows the voltage signals to stabilize when voltages are reapplied before the differential elements can operate. During commissioning, voltage stabilization is easily checked using the event report of the relay to make a record when the bank is energized.

Shunt Bank Control

With the X inputs from the bus and Y inputs from the tap for differential protection, only the X voltages can be used for voltage control. Set the relay so both voltage control schemes use the X inputs.

Having two voltage control schemes for one bank can be used to advantage. One can be set with narrower voltage limits and longer time delays. A large voltage excursion can be quickly controlled; reaction to smaller excursions can then be provided with additional delay. This reduces the overall frequency of bank insertion and removal.

Control and Protect a Capacitor Bank while Controlling a Reactor Bank

If a reactor bank must also be used to control the system voltage, one voltage control scheme can control the capacitor bank while the other controls the reactor bank. Separate timers with independent pickup and dropout timing, independent Raise Enable and Lower Enable inputs for each scheme, and programmable mask logic allow users to incorporate the relay in a wide variety of schemes.

Fuseless Shunt Bank Protection

Reference 2 discusses the advantages of fuseless banks. Some of the advantages include simplicity, size, lower losses, no nuisance fuse operations, no fear of case rupture from the energy in parallel units, and more sensitive protection. The protection can be more sensitive because the unbalance created by a loss of one unit is more observable. When n units in a series string of S units short, the voltage at the tap changes by -n/(S-n) per unit. Comparing this to Equation 3 of Table 1, we see that the tap point voltage change is approximately P times bigger for the series string! Since P can be 10 to 20, this is a substantial improvement, especially for large banks. In the 500 kV bank discussed below, there are P = 20 units per group and S = 38 groups in series, for 760 units per phase. This is well above the 613-unit minimum sensitivity of the relay determined earlier. Each unit is rated at 150 kVAR for a total of 114 MVAR per phase or about 377 amps per phase at 523.9 kV.

Using the guidelines of Reference 2, we can investigate a fuseless bank approach. The reference suggests a 60-amp current limit per string; a seven-string design is the result.

Each unit consists of a number of individual capacitors or sections, each having an individual voltage rating of about 1600 volts. The 523.9 kV rated voltage divided by 1.732 gives a string voltage of 302.5 kV per phase. Dividing this by 1600 volts per section implies that there will be about 302.5/1.6 = 189 sections in series per string per phase, no matter what size (kVA or voltage rating) units we use.

Beginning with the 0.15 volt minimum setting and assuming a 115 volt output from the voltage-sensing device, the relay sensitivity is 0.15/115 = 0.00130 pu. If one string had 200 sections in it, and one section shorted, the differential voltage developed would be about 1/200 = 0.005 pu, or over three times the relay sensitivity.

In the fused design, the relay can detect the loss of the second unit in one group. In the fuseless design, the relay can easily detect the loss of one section inside one unit!

Figure 13 shows one phase of a three-string fuseless shunt capacitor bank. The bank can be protected and controlled with three relays, marked 1, 2 and 3. Relay 1 handles the voltage control and differential protection for the left-hand string. Relays 2 and 3 provide side-by-side differential protection for the three strings. For every additional string, add another relay.

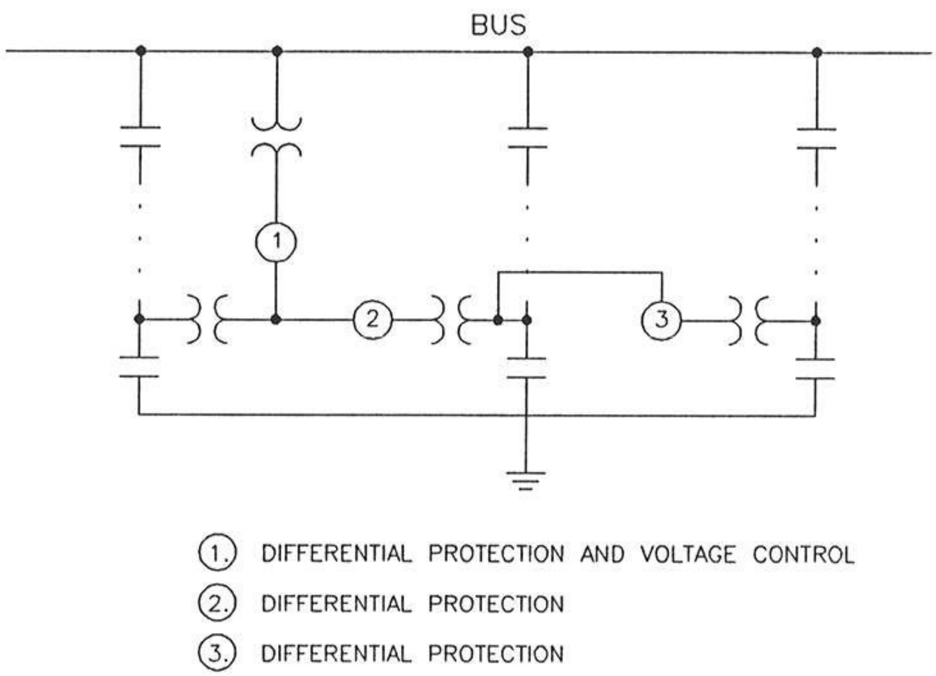


Figure 13: Fuseless Shunt Capacitor Bank Protection

It may be possible to set the tap-to-tap relays (e.g. 2 and 3) more sensitively, because voltage sources for the tap potentials are probably dedicated to capacitor protection. On the other hand, there may be some errors associated with the bus PT; these errors limit the sensitivity to which relay 1 can be set.

The beauty of dividing the bank into series strings (which fuseless designs permit) is that differential-protection sensitivity is no longer a critical issue in large banks.

The relays which operate or alarm indicate the string with a shorted unit. Relays 1 and 2 sense a shorted unit in the left string. Relays 2 and 3 sense a shorted unit in the middle string. Only relay 3 senses a shorted unit in the right string.

Voltage Measurements

Making a meaningful differential voltage measurement to within 0.15 volts on a scale of 0 - 150 volts requires control over sources of error measuring 0.001 pu or less. Significant errors can enter from grounding, mutual coupling, instrument transformer burdens, temperature, and other sources.

Grounding

Figure 14 is a single-phase schematic showing a wound PT or CCVT measuring the bus voltage and a wound PT measuring the tap voltage. The voltage measurement points (P,1) and (B,2) can be far apart in a large station.

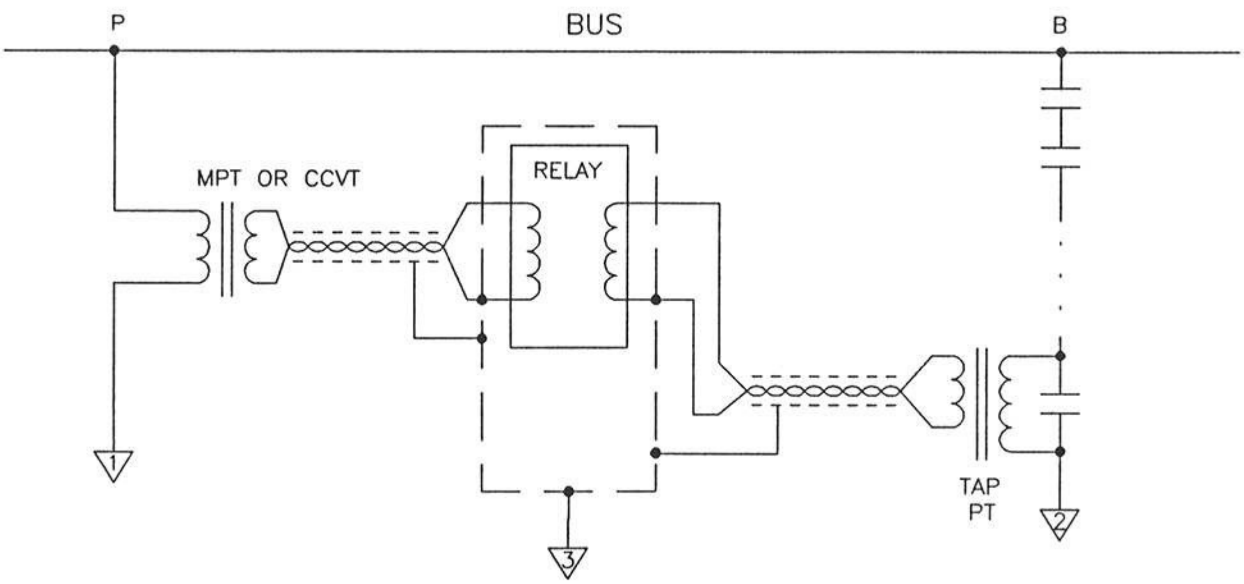


Figure 14: Ground References for Capacitor Protection

The bus device measures phase voltage with respect to the point on the ground mat shown by the ground symbol "1". The tap point measurement is made with respect to ground "2." Finally, the relay is inside the control house in a panel at ground potential "3." These grounds are at different potentials all the time, and can be far apart, even dangerous, during ground faults, even though all the equipment is connected to the same ground mat.

For safety, the secondaries of the potential devices must be grounded, e.g. at the control house.

For security, the secondaries must be grounded at one point only. If the secondary of the bus device is grounded at the bus as well as the control house, grounds 1 and 3 are connected together through one wire in the PT cable. Some or most of the potential difference between 1 and 3 adds to the voltage device output, producing an error at the relay input. The voltage error is primary current times some primary impedance, but appears in the secondary circuit without benefit of the PT ratio. This error can be very large indeed.

Even with the secondaries grounded only at one point, there is a source of error to consider. The bank divides the voltage between point "B" on the bus where the bank is connected and ground "2." The bus potential measurement is between the bus at point "P" and ground "1." We would like to assume that VP = VB and V1 = V2; however, currents flowing through bus and ground impedance make these unequal and introduce errors, especially during faults.

Mutual Coupling

Capacitive and magnetic induction can influence the secondary signals. The secondary circuits to the relays should be twisted to minimize magnetic induction and shielded to minimize capacitive induction. The shield should be grounded at one end only to prevent circulating currents in the shield wire during ground faults.

Regulation and Burdens

The regulation of instrument transformers is not ideal. CCVTs are of special concern. The impedance of the cabling between an ideal PT and a distant control house full of electromechanical relays can also be important.

The differential elements ignore phase, so phase regulation is not a concern. The relay has a convenient feature for balancing differential elements. The KSET command measures the voltage at each pair of inputs (e.g. VAX, VAY) and computes the proportionality constant required to zero the difference VAX - kA * VAY. This command can be used to adjust the constants whenever there are more than 20 volts on the inputs.

Burdens change, however. Relays may change their burdens when they pick up. New relays may be added, or existing relays may be taken out of service for maintenance. Imperfect regulation and changing burdens lead to differential error signals, which could be substantial enough to trip a sensitively-set voltage differential relay.

If the differential elements must have sensitive settings, dedicated instrument transformers should be seriously considered. These transformers should be located close to the bank, so all can measure voltage with respect to the same point on the ground mat.

Tap-to-Tap Differential Protection

In split banks and fuseless banks, tap-to-tap differential protection can be used, as discussed in Figure 13. The devices used to measure voltage at the taps are probably dedicated to capacitor bank protection, and therefore are not subject to output changes resulting from changing burdens. The devices may also have their primaries grounded at the neutral point of the bank, eliminating the ground "1"-ground "2" concern of Figure 14. Also, if the secondary cables from all tap-potential-measuring devices run to the control house together, there is a chance that sources of interference which influence the control wiring will influence all circuits the same way, minimizing errors.

Response to System Faults

As already explained, a ground fault could create undesired differential signals at the relay through several mechanisms.

The transient behavior of the potential measurements must also be considered. Although the instantaneous values of the bus and tap voltages should stay in exact proportion, the outputs of the CCVTs or MPTs may not, since the transient performance of the devices on the bus and tap may be different. Any significant voltage change, such as a close-in fault of any kind, will excite the possibly different transient responses of the measuring devices. This makes transient output from the differential elements possible due to differences in the transients.

The relay includes event recording, which is useful in measuring the duration of transients created by faults or switching. Observation is the best way to ensure that loss-of-potential blocking dropout delays and minimum trip and alarm times are set securely.

System Voltage Collapse Detection

Capacitor protection and control motivated the development of the protective relay treated in this paper. The large number of voltage elements, programmable logic, and precision suggest other applications. One possible application is load shedding for system voltage control. Recall that the relay provides two voltage control logic schemes. One could be used to control the same capacitor bank the relay protects. The other voltage control logic could be used to signal system voltage collapse. This might be used as a part of some remedial action to restore system voltage.

APPLICATIONS

Since the early 1960's, Bonneville Power Administration has been using its own voltage differential relay to protect grounded shunt capacitor banks. This voltage differential relay, designated the MTY, was designed by BPA engineer M. O. Tom. Reference 3 describes the MTY relay. The relay is in use on 115 kV, 230 kV, and 525 kV shunt capacitor banks. Like the new relay, the old relay detects blown fuses on cans by detecting a voltage difference between the bus voltage and tapped capacitor voltage. By detecting the blown fuses, the capacitor bank can be automatically removed from service if the voltage difference exceeds the limit of the particular group. This protects the individual cans from overvoltage stresses.

In October 1989, BPA began a project to add two new grounded wye connected shunt capacitor sections to BPA's Raver Substation, located 25 miles east of Auburn, Washington. The additional banks will aid voltage support in the Seattle, Washington area. Figure 2 is a photograph showing part of the new bank.

The MTY relay was not used in this project for several reasons. First, the relay is discontinued, and no longer available. Second, due to the size and configuration of the capacitor sections, a more sensitive relay was necessary. Third, some shortcomings of the MTY needed correction to ensure higher reliability.

The new relay described in this paper was specified with voltage differential capabilities, as well as additional features. One of these is a time-overvoltage function. Another feature is automatic voltage control. Typically, voltage control is a separate scheme. However, since it requires the same voltage source, it could be a part of the new relay, making the overall scheme very simple to design and build. In addition, the new voltage control scheme responds to the average of the three phase-to-neutral voltages, whereas the old schemes monitor one phase-to-phase voltage.

Figure 15 shows the configuration at Raver last year. Shunt reactor banks are available at both the north and south buses. The single section of shunt capacitors was at the south bus. The figure shows two MTY voltage differential relays available for the capacitor bank. Both relays monitored the tap point voltage, but the relays obtained bus voltages from different line-side CCVTs. Line-side PTs had to be used because three-phase voltages were not available from the buses. A separate overvoltage relay was required to monitor tap voltages, to detect gross overvoltage conditions at the tap.

Figure 16 shows the new configuration with the two new sections (2 and 3) added. Two circuit breakers were added to make a separate bus section for the three capacitor groups. The two new groups are controlled by individual circuit breakers and have 3 mH current-limiting reactors connected in series to limit back-to-back switching currents. Next year, the Section 1 circuit switcher will be replaced by a circuit breaker and current-limiting reactor, making it identical to the other two sections. The addition of two more CPTs per phase on each bus provides three-phase bus potentials for the differential relays and removes the dependence of bank protection on whether or not various transmission lines

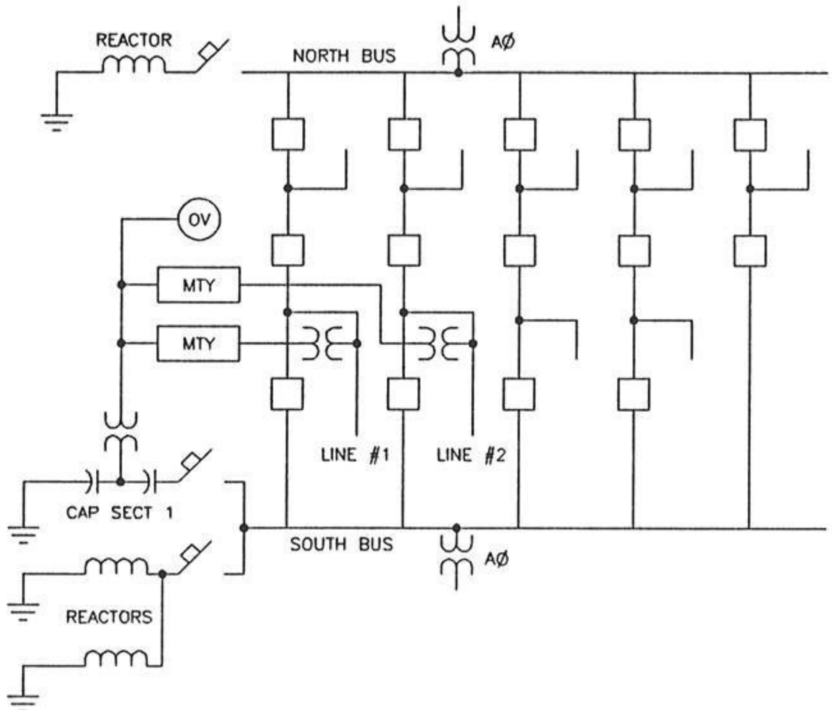


Figure 15: Raver Substation 1989

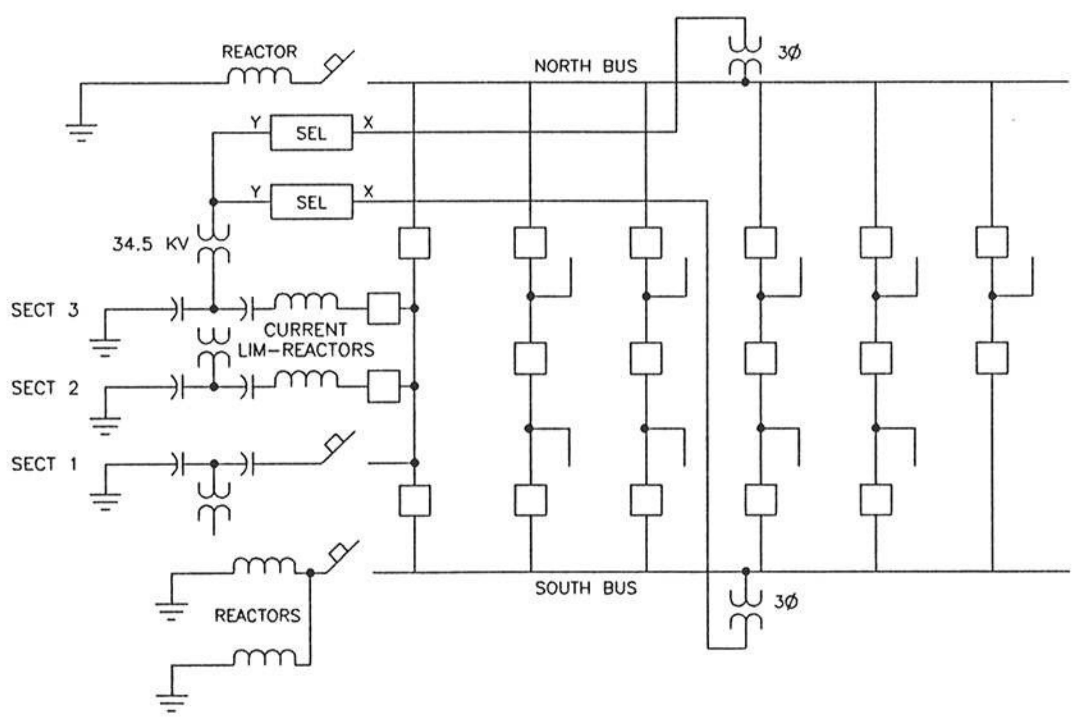


Figure 16: Raver Substation 1990

are in or out of service. Because each SEL-187V relay contains overvoltage protection for both the X and Y groups of inputs, the separate overvoltage relay is no longer required.

Not shown in Figures 15 or 16 are the voltage control equipment which consisted of a under/overvoltage relay monitoring a phase-to-phase voltage, a number of time-delay relays to time the insertion and removal of the banks, and some latching relays. SEL-187V relays eliminate all but the automatic/manual control latching relay. Figures 20 and 21 show the old and new capacitor control and protection panels.

Figure 17 shows more details of the overall capacitor bank protection. A pair of SEL-187V relays provides redundant protection and control for each capacitor bank section. SEL-BFR breaker failure relays cover the two bus breakers and the two (plus one future) bank breakers. A redundant set of Basler BE-51 phase and ground overcurrent relays monitors the sums of the currents into the capacitor groups and provides backup protection. The diagram also shows the CTs for the north and south bus differential protection schemes.

Raver dc Control Logic

Figures 18 and 19 are the trip and close dc schematics.

The trip circuit mainly consists of two SEL-187V relays and an automatic-manual latching relay, labeled "AM." Either relay can trip the circuit breaker for fault conditions or voltage-lowering effects. One TRIP contact from each relay connects directly to the tripping bus of the circuit breaker for the associated capacitor bank section. The other TRIP output from each relay energizes the reset coil of the AM latching relay to force manual control for any relay trip. Programmable output contacts "A2" are paralleled so either relay can lower the system voltage by tripping the bank, as long as the AM relay is set in the automatic control state. Automatic/manual supervision is provided two ways: by the AM contact in series with the paralleled A2 contacts and the AM contact which controls the Lower Enable inputs (LE1, LE2) to the relays. Figure 18 also shows the mask programming for the TRIP and A2 (Lower Voltage) outputs. The relays trip for instantaneous or time-delayed overvoltage conditions at the bus (X59I, X59T) or at the tap (Y59I, Y59T). They also trip after a short time delay for excessive differential voltage associated with any phase (87TD).

The voltage control logic outputs are programmed onto the A2 output using mask MA2, also shown in Figure 18. Recall there are two voltage-control logic schemes: 1 and 2. In this application, both are programmed to follow the X (bus) potentials by using a setting of VSS=X, shown later. The delayed-high-voltage output conditions from the two schemes are VHD1 and VHD2: these are programmed into mask MA2 so output A2 asserts whenever either scheme calls for lower voltage. Having two schemes for each section allows faster insertion of sections for large voltage drops and slower insertion for smaller voltage drops, if desired.

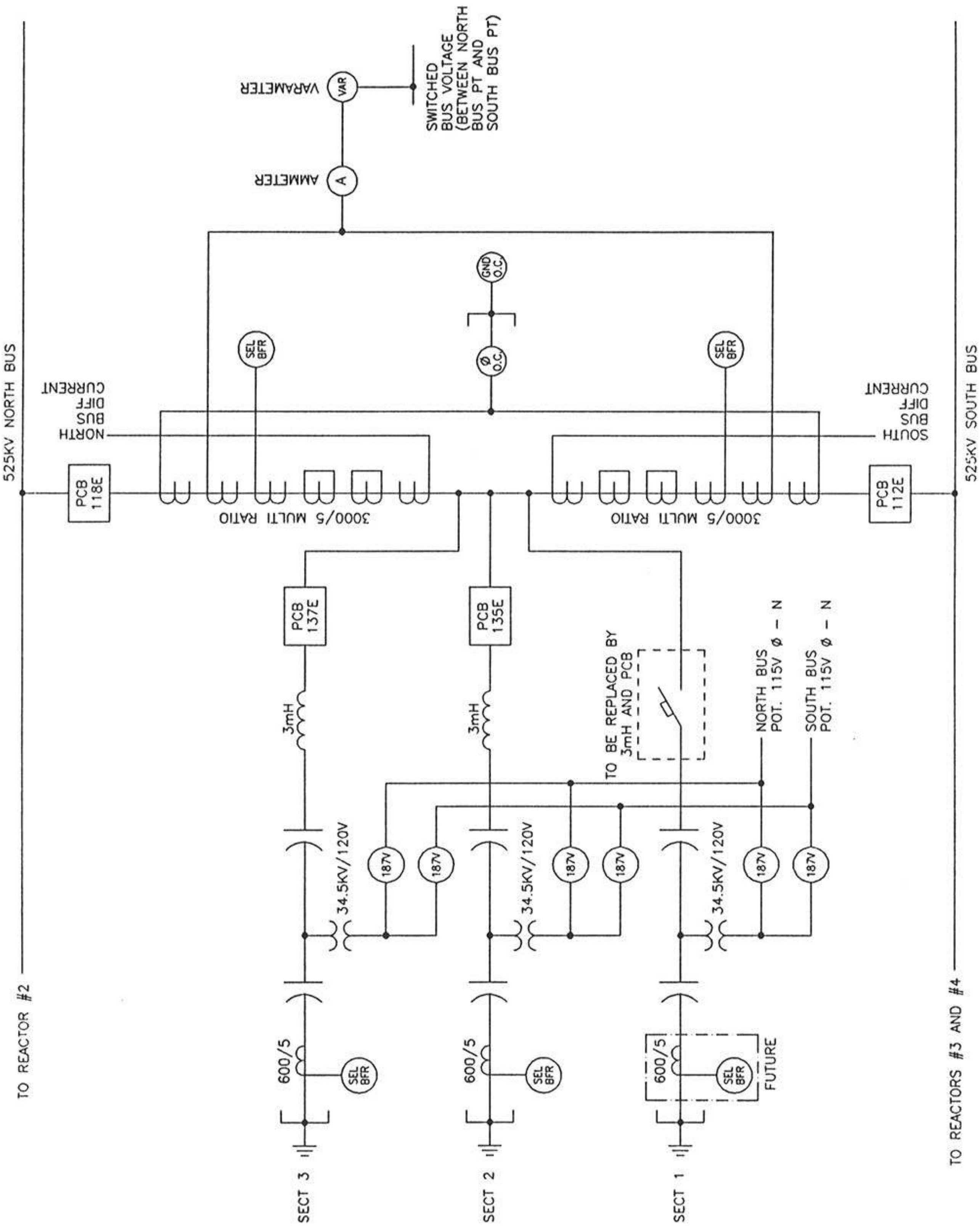


Figure 17: Raver Capacitor Bank Control and Protection

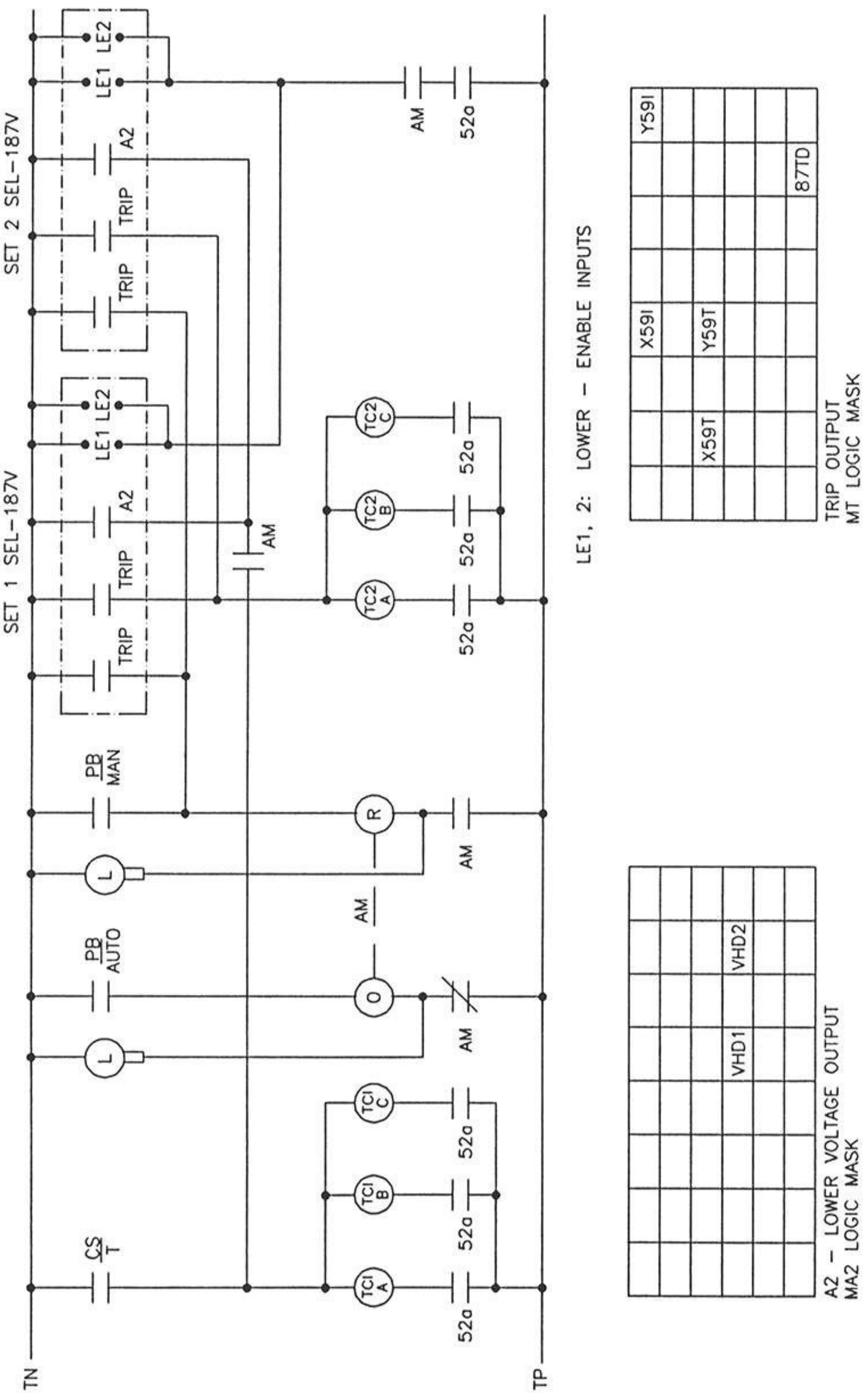
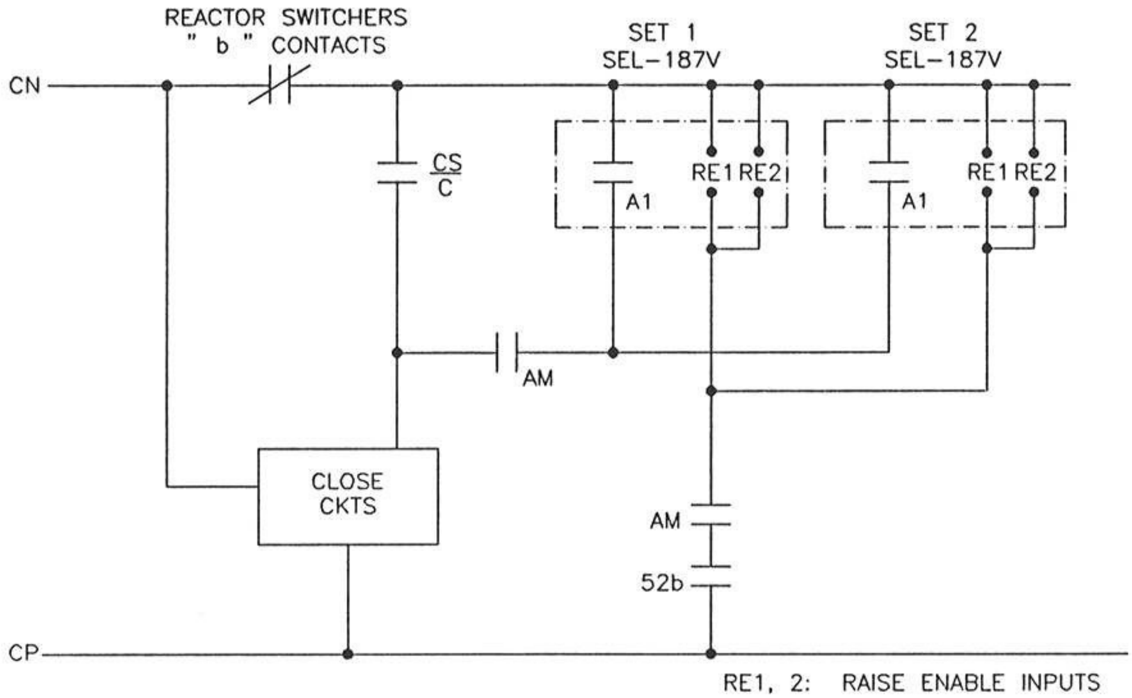


Figure 18: Trip Schematic



					VLD1		VLD2

A1 – RAISE VOLTAGE OUTPUT
MA1 LOGIC MASK

Figure 19: Close Schematic

Another possibility is to separately control the RE1 and RE2 inputs from SCADA, so voltage control can be deselected, or either of two schemes selected, depending on system conditions. Still another possibility is to control the voltage-control inputs from other auxiliary contacts in the substation, so the voltage-control program depends on, for example, other lines in or out of service, or possibly loading of other lines.

The close schematic of Figure 19 shows the A1 contacts from the two relays in parallel and connected to the close bus through an AM contact. An AM contact and the 52b must be closed to energize the raise-enable inputs (RE1, RE2) of both relays. The A1 output relay mask MA1 contains the voltage control outputs which indicate the system voltage has been low for set times: VLD1 and VLD2. As in the case of the trip circuits, the voltage control logic could be controlled locally or remotely through VLD1 and VLD2.

Each new section is rated 324 MVAR at 523.8 kV. Each section consists of 20 parallel cans in each layer and 38 series layers. Each can is rated at 7960 volts and 150 kVAR. Four layers above the common point on each section, a 34.5 kV potential transformer is located on each phase. This produces the tapped capacitor potential used in the voltage differential scheme. Each new capacitor section is protected by a 550 kV ABB ELF power circuit breaker. Also included is a 3 mH current limiting reactor, per phase, to limit back-to-back switching inrush to less than 20 kA.

Setting Considerations

Section 1 at Raver was designed when the system voltage operated near 500 kV. It has 36 groups in series; each group has 15 units rated at 7960 volts. Therefore, the rated operating voltage is 36 * 7960 = 286,560 volts per phase, corresponding to a system voltage of 496.3 kV. The system voltage was later raised to 535 kV, and runs at 550 kV or higher at times. The MTY relays were set as follows (assuming a bus voltage of 550 kV):

CONDITION	#FUSES	dV (sec)	OVERVOLTAGE(pu)
Normal	0.0	0.00	1.108
Alarm	2.5	0.62	1.322
Trip	3.5	0.94	1.433

Obviously, fuses blow in integral numbers. The fractional notation of number of fuses indicates only that the differential voltage condition dV shown is midway between the differential voltages produced by integral numbers of fuses. For instance, the 0.62 volt dV value is midway between the voltages corresponding to two and three fuses out in the same group.

Overvoltage limits for alarming and tripping of 15% and 25% would have been preferred, but nuisance alarms and trips occurred at lower settings with the MTY. Therefore, the bank can be operated at voltages well in excess of 110% without anyone knowing it.

The new SEL-187V relay and the use of dedicated PT wiring from the upgraded bus CVTs should offer some improvement. If we use 0.24 and 0.42 volts secondary for the alarm and trip points, the overvoltages possible on the cans remaining in a group reduce to about 1.18 for alarm and 1.25 for trip.

In the new sections, there are 20 units per group and 38 groups in series, so the rated voltage is 38 * 7960 = 302,480 volts per phase, corresponding to a system voltage of 523.9 kV.

The section settings for the new relay will provide the following protection (again at 550 kV system voltage):

CONDITION	#FUSES	dV (sec)	OVERVOLTAGE(pu)
Normal	0.0	0.00	1.050
Alarm	1.5	0.24	1.133
Trip	2.5	0.42	1.195

The 0.24 volt minimum setting must accommodate the 0.15 minimum recommended differential setting discussed earlier, plus any system measurement errors.

The actual settings applied by the relay (as output by the relay setting procedure) are:

```
=>>set

SET clears events. CTRL-X cancels.
Enter data, or RETURN for no change

ID    : RAVER REACTIVE GROUP 1, CAP SECTION 2  ?
X59I  : O/V Thres, X (Volts)....... = 150.00   ?        (This is 124% of rating.)
X27L  : U/V Thres.................. = 10.00    ?
Y59I  : Y.......................... = 131.59   ?        (This is 124% of rating.)
Y27L  : ........................... = 10.00    ?

X59PU: Time O/V Pickup Thres, X (Volts) = 133.09   ?    (110% of rating.)
X59D  : Time Dly, X (cyc).......... = 3600     ?
Y59PU: Y........................... = 116.75   ?        (110% of rating.)
Y59D  : ........................... = 3600     ?
VSS   : Selection Scheme (I,B,X)... = X        ?        (Bus potentials for both
                                                         voltage control schemes.)

59P1  : Scheme 1 O/V (Volts)....... = 128.17   ?   (555 kV or 106% of rating.)
THP1  : O/V Dly PU (cyc)........... = 1800     ?
THD1  : Dly DO..................... = 300      ?

27P1  : Scheme 1 U/V (Volts)....... = 120.09   ?   (520 kV or 99% of rating.)
TLP1  : U/V Dly PU (cyc)........... = 180      ?
TLD1  : Dly DO..................... = 300      ?

59P2  : Scheme 2 O/V (Volts)....... = 128.17   ?
THP2  : Dly PU (cyc)............... = 1800     ?
THD2  : Dly DO..................... = 300      ?
```

```
27P2 : Scheme 2 U/V (Volts)....... = 120.09   ?
TLP2 : U/V Dly PU (cyc)........... = 180      ?
TLD2 : Dly DO..................... = 300      ?

KA   : 87A ratio adjustment....... = 1.140    ?
KB   : ........................... = 1.140    ?
KC   : ........................... = 1.140    ?

87AT : 87A Trip Thres (dv, Volts). = 0.42     ?
87AA : 87A Alarm Thres............ = 0.24     ?
87BT : ........................... = 0.42     ?
87BA : ........................... = 0.24     ?

87CT : ........................... = 0.42     ?
87CA : ........................... = 0.24     ?

87TPD: 87T PU Dly (cyc)........... = 10       ? (Delay for fuse coordination.)
87TDO: DO Dly..................... = 300      ?
87APD: 87A PU Dly................. = 200      ?   (Delay for alarm security.)
87ADO: DO Dly..................... = 0        ?

XLOPD: LOP DO Dly, X (cyc)........ = 10       ?
YLOPD: ........................... = 10       ?
LOPD : LOP DO Dly, X or Y......... = 20       ?       (Ensure pots stabilize.)
LOPE1: Scheme 1 enable (Y/N)...... = Y        ?
LOPE2: ........................... = Y        ?

TIME1: Port 1 timeout (min)....... = 5        ?
TIME2: ........................... = 0        ?
AUTO : Auto port (1,2,3).......... = 2        ?
RINGS: (1-30)..................... = 3        ?
```

```
New settings for: RAVER REACTIVE GROUP 1, CAP SECTION 2

X59I = 150.00   X27L = 10.00    Y59I = 131.59   Y27L = 10.00
X59PU= 133.09   X59D = 3600     Y59PU= 116.75   Y59D = 3600     VSS  = X
59P1 = 128.17   THP1 = 1800     THD1 = 300
27P1 = 120.09   TLP1 = 180      TLD1 = 300
59P2 = 128.17   THP2 = 1800     THD2 = 300
27P2 = 120.09   TLP2 = 180      TLD2 = 300
KA   = 1.140    KB   = 1.140    KC   = 1.140
87AT = 0.42     87AA = 0.24     87BT = 0.42     87BA = 0.24
87CT = 0.42     87CA = 0.24
87TPD= 10       87TDO= 300      87APD= 200      87ADO= 0
XLOPD= 10       YLOPD= 10       LOPD = 20       LOPE1= Y        LOPE2= Y
TIME1= 5        TIME2= 0        AUTO = 2        RINGS= 3
OK (Y/N) ? y
Please wait...
Enabled

RAVER REACTIVE GROUP 1, CAP SECTION 2      Date: 1/1/90      Time:
01:16:04

=>>
```

The two voltage control schemes are set identically for now, but may be set differently in the future, enhancing voltage control scheme responsiveness.

The logic mask settings for tripping and raise/lower control were discussed earlier and are included in Figures 18 and 19. Output A5 is programmed as an alarm output with mask MA5. 87AD is the only bit included. It is the time-delayed output of the alarm differential elements. The time delay pickup for alarming is set to 200 cycles (87APD = 200), so the sensitive alarm threshold of 0.24 differential volts secondary does not cause nuisance alarms.

The relay generates event reports for any trip and any other conditions programmed into a mask for event report triggering (MER). Initially, we will trigger event reports on any overvoltage condition, differential trip or alarm (before their time delays), and on all raise and lower commands. Thus, the bits included in MER are: X59P, Y59P, VHD1, VLD1, VHD2, VLD2, 87T, and 87A.

CONCLUSIONS

The new relay simplifies the design of grounded shunt capacitor control and protection schemes. At the same time, it provides better protection through the use of the differential voltage measurement principle and careful signal processing. Because it is essentially a programmable voltage relay with six inputs, many timers, and mask logic, it is suitable for other voltage-control and protection applications. Adjusting the balance of the relay is simplified by the KSET command, and inspection of all voltages is possible via command. The event reporting feature captures any desired operations or conditions because its triggering conditions are mask-programmable.

The 500 kV application at Raver Substation demonstrates many of the relay features and the simplicity of the installations. The application also indicates that one blown fuse in a bank of 760 units per phase produces very little differential signal for a relay to measure. Sources of error outside the relay may mask this differential signal, suggesting the consideration of bank designs which use fewer units or different arrangements (e.g. fuseless series strings.)

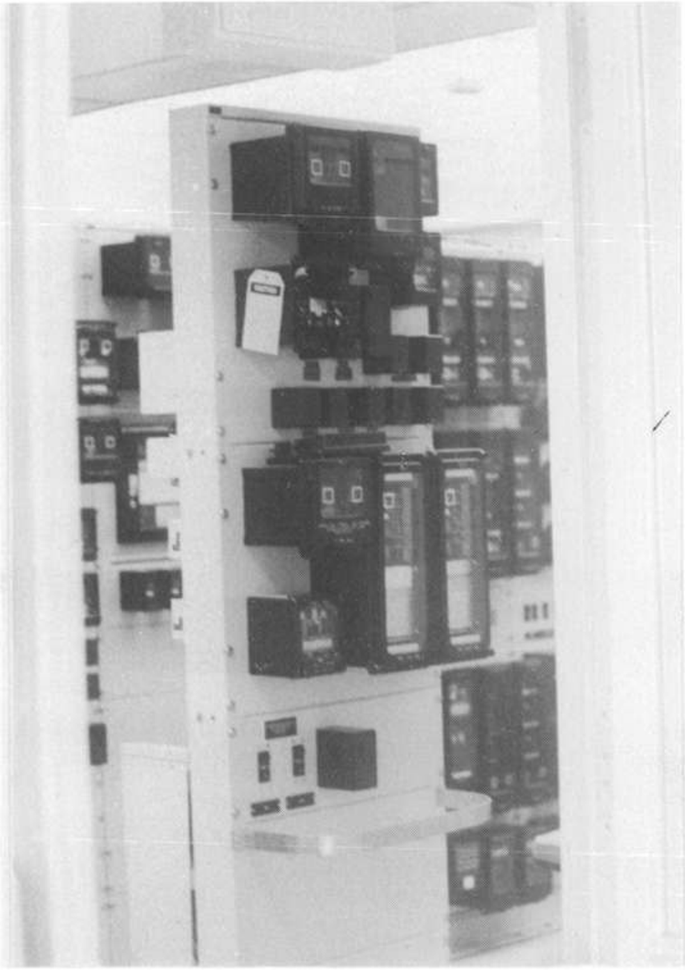


Figure 20: Original Capacitor Control and Protection Panel

Figure 21: New Capacitor Control and Protection Panel

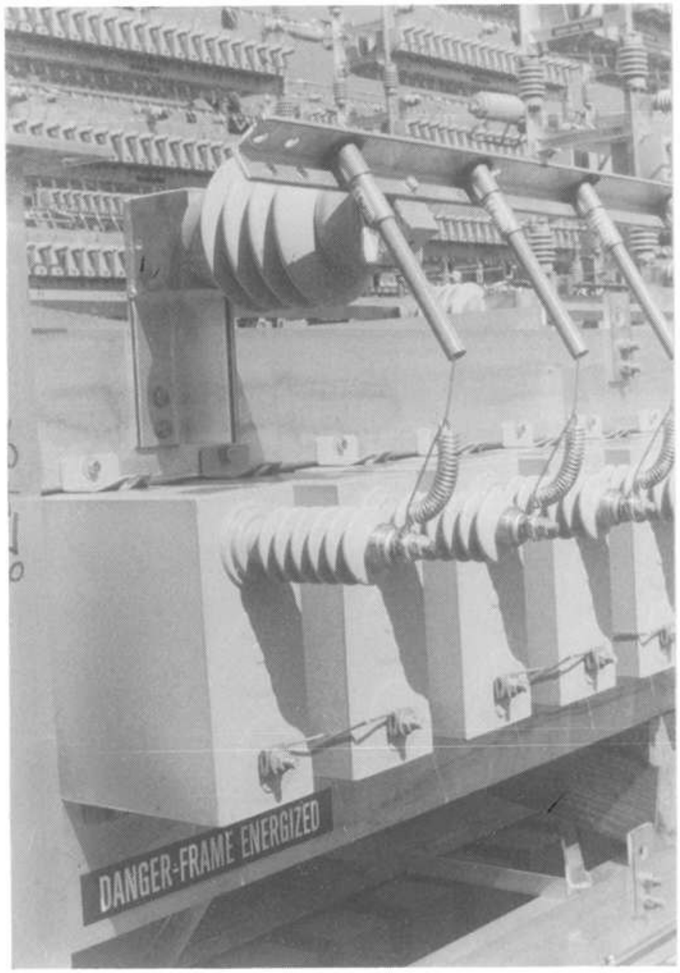


Figure 22: Close-up of Units and Their Fuses

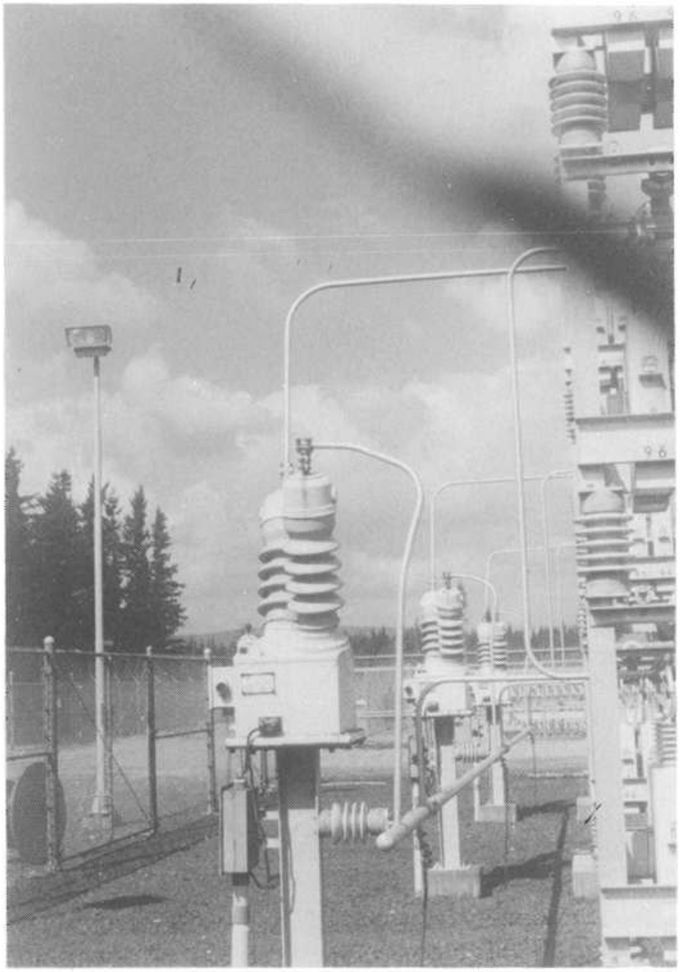


Figure 23: 35 kV PTs Measuring Tap Voltages

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